SSCL-279

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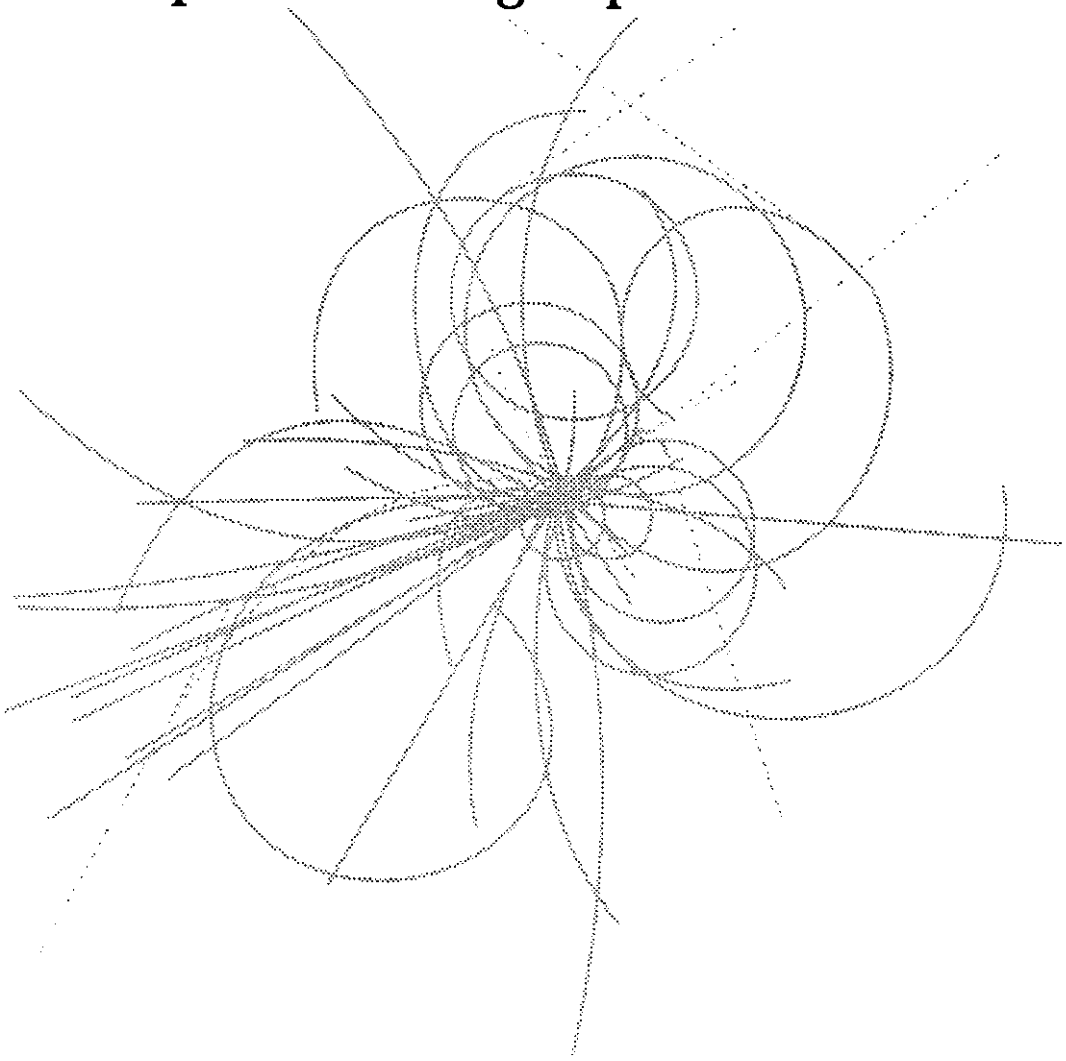
Superconducting Super Collider Laboratory



Simulation of the SSC Refrigeration System Using the Aspen/SP Process Simulator

J. Rasson and J. Dweck

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INTRODUCTION

The SSC Magnet must maintain at a super conducting temperature of 4 K. The proposed refrigeration cooling processes consist of fairly simple closed cycles which take advantage of the Joule-Thompson effect via a series of expansions and compressions of helium gas which has been precooled by liquid nitrogen. The processes currently under consideration consist of three cycles, the 20 K shield cooling, the 45 K helium refrigerator and the helium liquefier. The process units which are to be employed are compressors, turbines, expanders, mixers, flashes, two stream heat exchangers and multiple stream heat exchangers. The cycles are to be operated at or near steady state.

Due to the large number of competing cooling sector designs to be considered and the high capital and operating costs of the proposed processes, the SSC Laboratory requires a software tool for the validation and optimization of the individual designs and for the performance of cost-benefit analyses among competing designs. Since these processes are steady state flow processes involving primarily standard unit operations, a decision was made to investigate the application of a commercial process simulator to the task.

Several months of internal evaluations by the SSC Laboratory revealed that while the overall structure and calculation approach of a number of the commercial simulators were appropriate for this task, all were lacking essential capabilities in the areas of thermodynamic property calculations for cryogenic systems and modeling of complex, multiple stream heat exchangers. An acceptable thermodynamic model was provided and a series of simple, but

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representative benchmark problems developed. The model and problems were provided to three software vendors. Based on the results of the benchmark tests, the ASPEN/SP process simulator was selected for future modeling work.

ENHANCEMENT OF THE ASPEN/SP PROCESS SIMULATOR

While ASPEN/SP process simulator has the basic flowsheeting capabilities and unit operation models required for this task, several enhancements were needed to facilitate development of the SSC process models. These enhancements can be classified into three categories: thermodynamic models, two-phase flash algorithm, and unit operation models. Each is discussed below.

Thermodynamic Models

Unlike most chemical processes, the SSC cooling sector involves the flow of only pure components. Essentially pure helium is the fluid used in the cycles, while pure nitrogen is used external to the cycle to cool the helium to the maximum temperature at which JouleThompson cooling can take place. While the lack of mixtures should simplify the physical property calculations, the peculiarities of helium actually lead to greater physical property problems than for even fairly complex chemical systems.

Nitrogen does not exhibit any unusual behavior and, as such, is fairly easily modeled via conventional equations of state. For the purposes of this work, a highly accurate 32-term variation of the BWR equation of state developed by[1] Jacobsen is employed. This equation is valid from 63.15 to 1900 K and pressures up to 1000 bar. The uncertainties in the calculated temperatures are under 0.5% while the enthalpy is within 3.0 joules/k-mole across the entire range. Calculation times are fairly long owing to the difficult nature of the root finding procedure for this equation.

Helium exhibits phase, enthalpy and transport behavior unlike any other substance. Liquid helium forms two distinct phases, the normal fluid and the superfluid. The specific heat decreases with temperature to about 2.5 K, then increases dramatically to the lambda point (2.172 K), then decreases dramatically. The thermal conductivity of the normal fluid actually decreases with decreasing temperature, which is similar to the behavior of a gas. On the other hand, the thermal conductivity of the superfluid is so high, that bubble formation cannot take place during boiling. The superfluid also displays a behavior termed superfluidity, where it acts as if it had zero viscosity.

To provide for the simulation of the proposed cycles, a physical property model capable of accurately calculating the liquid and vapor phase fugacities, enthalpies, entropies and densities of helium at temperatures from 0.8 K to 500 K and pressures up to 3,000,000 N/sqm is required. Since the majority of the proposed designs operate above the lambda temperature of helium (2.172 K), the first model which was implemented is the well-known[2] McCarty model, distributed by the National Bureau of Standards. This model was designed as a standalone program for the calculation of vapor and liquid helium properties. While the model can accept various input specifications, the only specifications which are useful for ASPEN/SP are temperature and pressure.

When the temperature and pressure are specified, the model determines the phase of the helium and returns a list of properties, including density, enthalpy, entropy and heat capacity. In ASPEN/SP, however, the flash algorithm is responsible for determining the phase of the system. In order to make this determination, the flash algorithm requires the fugacity and enthalpy of both the liquid and vapor phases at the specified condition. If the system does not exist in one of the states at the condition, extrapolated hypothetical values must be returned by the physical property models. Since the McCarty model is not designed to return data for hypothetical phases, modifications had to be made.

The equation of state has multiple roots, two of which represent either the actual or extrapolated liquid and vapor roots. The root finding algorithm of the original McCarty model, which employs a Newton-Raphson approach, is not robust enough to locate the extrapolated root in the general case. The cause of this problem was isolated to the division of the temperature-pressure plane into four regions, each with different coefficients, to enhance the accuracy of the model. The function is not smooth across the boundaries, limiting the effectiveness of the Newton-Raphson algorithm when the boundaries are crossed. This problem was solved by modifying the Newton-Raphson algorithm to use the analytical derivatives to calculate an approximate next value of the iteration variable, then recalculating the derivative numerically via finite difference between the new point and the original point. This derivative then is used by the Newton-Raphson technique to determine the actual new value. This approach while only slightly slower does eliminate the robustness problems.

For temperatures below the lambda point, a proprietary model developed by Air Products was implemented. This model also appears to perform reliably above the lambda point, although errant phase determinations did result when applying this model near the critical point. This problem was not observed with the ASPEN/SP implementation of the McCarty model. The two models are implemented in such a fashion that the user can select either model by setting a single input parameter.

Two-Phase Flash Algorithm

The-two phase flash algorithm contained in ASPEN/SP is extremely robust and efficient for a wide variety of chemical systems over broad ranges of temperature and pressure. However, in order to accommodate the temperature range encountered in the proposed cooling sector designs and the temperamental nature of the McCarty thermodynamic model, two minor modifications were required. First, the lower temperature bound was changed from 50 K to 2. 1 K. (For the later work, the bound was lowered to 0.5 K.) Second, functions were developed to aid in the generation of initial temperature estimates for specified pressure - enthalpy flashes.

The initial estimate functions are necessary because of the highly irregular nature of the enthalpy of the hypothetical vapor root solution to the McCarty equation. In certain circumstances, the enthalpy of the hypothetical vapor actually will decrease with increasing temperature. This can cause the erroneous calculation of a high temperature vapor instead of a low temperature liquid at a particular pressure and enthalpy if a poor initial temperature estimate is selected. The initial estimate functions are based on regressed fits of the saturated liquid and vapor enthalpies of helium as a function of pressure.

Unit Operation Models

In addition to the two-phase flash algorithm enhancement described above, three unit operation enhancements were required to simulate the proposed designs. These three enhancements involve the development of user subroutines to facilitate off-design calculations with the turbine, robustness improvements for the two stream heat exchanger and the development of a multiple stream heat exchanger model. Each of these enhancements is discussed below.

When a turbine is operated at other than the design pressures and flow rate, the efficiency is different from the design efficiency. This variation in efficiency is described via a turbine curve. The user subroutines function by calculating the inlet nozzle diameter for the turbine at the design condition, assuming choke flow. The efficiency in off-design conditions then is computed as a fraction of the design efficiency via a look-up of a turbine curve at the desired condition, given the inlet nozzle diameter. A subroutine which calculates the speed of sound in helium was developed to facilitate this calculation.

The two-stream heat exchanger algorithm needed minor enhancements to handle certain types of phase transitions in the helium and to facilitate heat leak calculations. For chemical systems involving mixtures, the system must pass through a two-phase region between the vapor and liquid states. For pure components, however, a supercritical fluid which is at a pressure above the critical pressure, and is cooled at constant pressure can undergo an immediate transition to a saturated liquid without passing through the two-phase region. This behavior is observed in several of the heat exchangers and necessitated a modification to the two stream heat exchanger phase transition logic. The exceedingly low temperatures and odd geometries of the heat exchanger necessitate a provision for heat leak calculations. A capability to specify either a positive or negative heat leak as a fraction of the total heat transferred was added to the two-stream heat exchanger model.

A significant amount of effort was expended in the design of a multiple stream heat exchanger algorithm. Multiple stream heat exchangers are quite complex, involving the splitting of each feed stream into a number of flows which are exchanged in a countercurrent fashion against the opposite feed streams in a series of channels. Each hot stream flow contacts two cold stream flows simultaneously and visa versa. A certain fraction of the heat exchanger areas is devoted to each type of exchange.

Two algorithms were designed to model these exchangers. The first considers the area distribution inside the exchanger and simultaneously calculates the various types of exchanges, combining the outlet flows to achieve the final temperatures. The second is a highly simplified algorithm, referred to as the lumped-approach, which considers the exchanger to be a series of two stream heat exchangers. At the cold side, the coldest feed stream is heated against the combined hot streams, until the stream reaches the temperature of the next coldest feed stream. At this point, the two cold streams together are heat exchanged against the combined hot streams. The hot streams are treated analogously. That is, the hottest stream is cooled against the combined cold streams until the stream reaches the temperature of the next hottest stream. At this point, the two hot streams together are exchanged against the combined cold streams.

For the purposes of this work, the simplified, lumped-approach algorithm was adopted. This approach imposes a number of limitations upon the model, including the

uniformity of outlet temperatures on each side, the specification of a single heat transfer coefficient for all phase regimes, imprecise determination of pinch-point conditions, and limited applicability to off-design and rating situations. Independent specification of pressures and physical property methodology for individual streams are allowed and have been implemented.

The algorithm which has been implemented has a great deal of flexibility, allowing the specification of either the hot or cold stream outlet temperature, the exchanger duty, the minimum approach temperature or the overall exchanger area. The algorithm begins by calculating the overall heat duty and temperature at which each of the streams on either side begin to participate in the heat exchange. The first three types of specifications then are straightforward, involving no iterative calculations. The overall heat duty is the primary iteration variable for the minimum approach and area specifications. The heat duty is a superior iteration variable to the temperature due to the linear nature of the convergence and the elimination of convergence difficulties associated with phase transitions of pure components.

The multiple stream heat exchanger algorithm has performed very well, converging reliably and efficiently for all of the cases which have been tried. All of the specification options have been exercised and shown to produce consistent results.

EXAMPLE APPLICATION

While most of the cooling sector designs which have been simulated are proprietary, the simulation of a sample design can be discussed. Figure 1 is a simulation flowsheet of the combined 20 K shield and 4 K refrigerator for the sample design. This flowsheet contains ten two stream heat exchangers and assorted compressors, turbines and heaters. The nitrogen precooling has been neglected and the multiple stream heat exchangers have been represented as groups of two stream heat exchangers.

The ASPEN/SP input file for this simulation is contained in Figure 2. The special cryogen physical property option set has been employed. The simulation is performed in rating mode, with the areas of each of the heat exchangers being specified. Since the flowsheet forms a series of complex loops, tear streams have been specified and estimated flow rates and phase conditions specified. The tear streams are to be converged simultaneously.

Representative simulation results are contained in Figures 3 and 4. Figure 3 is a plot of the temperature profile in heat exchanger EXR5, which subcools a high pressure liquid stream against a low pressure vapor stream. The pronounced curvature of the hot stream cooling curve results from the unusual temperature variation of the helium heat capacity in the near-critical region. Figure 4 is a plot of the temperature difference profile in exchanger EXR5. The peak in this curve results from the curvature of the hot stream cooling curve. Figure 5 is an excerpt of the stream report for the simulation which contains the hot outlet stream from exchanger EXRS. The tear streams were converged in nine overall flowsheet iterations in approximately four hours on a 16 MhZ, 386 PC.

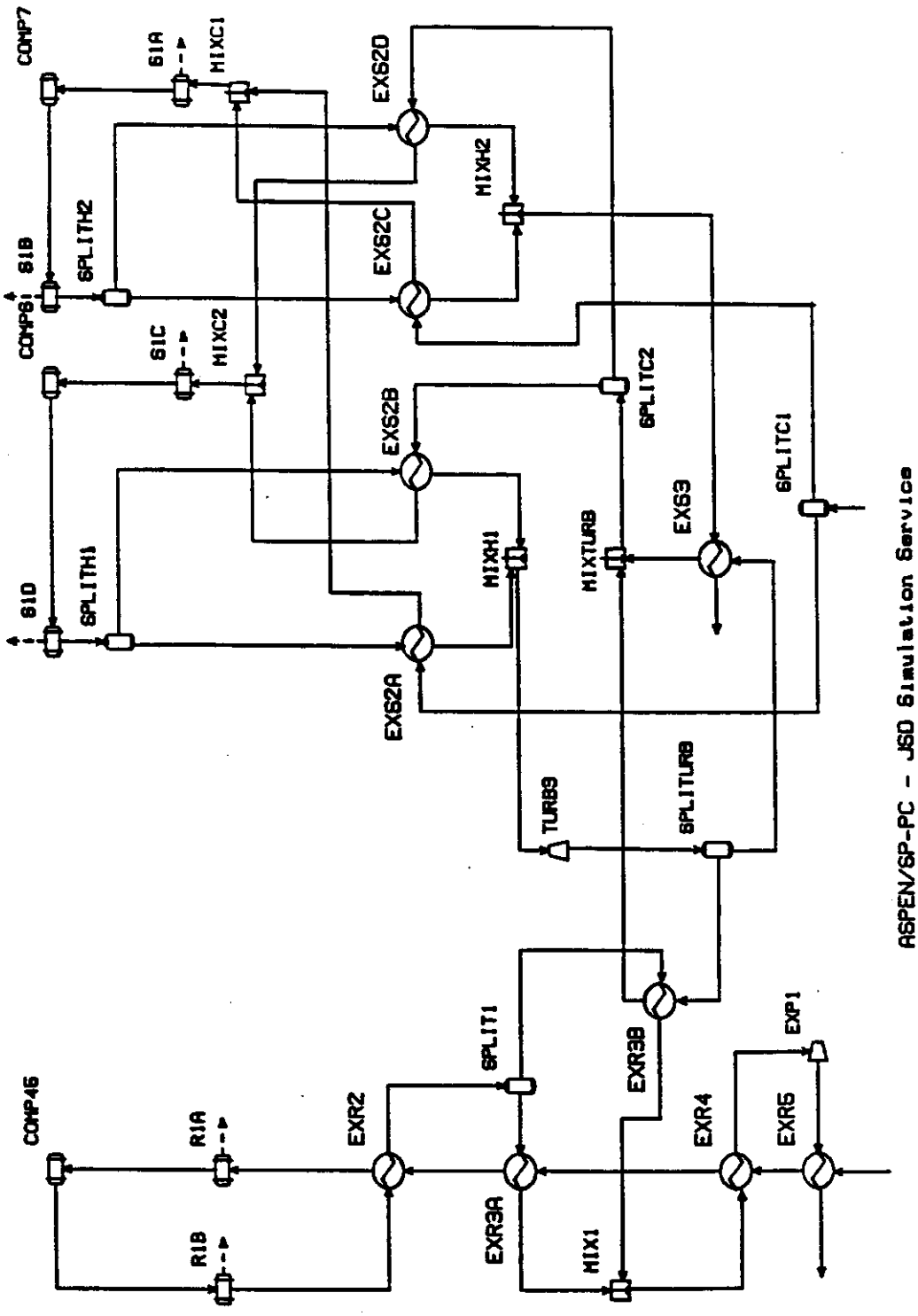

Figure 1. Simulation flowsheet of combined 20K shield and 4K refrigerator.

```
NEW
;:MAIL (ON BATCH JOB;DO YOU WANT MAIL(Y), NOTIFY(N) Y/N) =N
;:OLDID=BASE
;:NEWID=BASE
;:DEDETE FILES (EXCEPT .LOG .HIS .REP .INP  G BUILDS PLD; Y/N/G) =Y
;:VERSION (REFERS TO TEST(Y) OR PROPDUCTION(N))=N
;:BUILD A NEW INPUT TRANSLATOR (Y/N)=N
;:PDF LENGTH (400 MAX) = 250
;:QUEUE (B:BATCH_2, S:SYSSBATCH, H:HIGH_SPED)=S
;:SUBMIT (Y IF IMMEDIATE, N IF SPECIFYING TIME)=Y
;:KEY = USRPP1A                                ARG = CRYOGEN
;:END VAX/VMS PROCS
;
TITLE 'SIMPLIFIED CRYOGENIC REFRIGERATION CYCLE'
;
DESCRIPTION &
  ' SSC REFERIGERATION CYCLE BASE CASE SPECIFIED UA. INTEGRATED UA'
;
HISTORY  MSG-LEVEL  PROPERTIES=2  STREAMS=8
RUN-CONTROL  MAX-ERRORS=200
;
IN-UNITS  SI  PRES=ATM
OUT-UNITS SI  PRES=ATM
;
COMPONENTS  NITROGEN  NITROGEN / HELIUM  HE-4
;
PROPERTIES  SYSOP17
;
FILES  USRPP1A  CRYOGEN
;
PROP-SOURCES
    GLOBAL  CRYOGEN  COMPS=ALL
;
FORMULA  HELIUM  HE
;
DEF-STREAMS CONVEN  ALL / HEAT QR1A QR1B QS1A QS1B QS1C QS1D
;
;
;
FLOWSHEET 4K
    BLOCK  SPLITURB  IN =246            OUT = 256  236
    BLOCK  EXR5      IN = 170  182      OUT = 172  128
    BLOCK  EXP1      IN = 118           OUT = 170
    BLOCK  EXR4      IN = 116  128      OUT = 118   126
    BLOCK  SPLIT1    IN = 114           OUT = 114A  114B
    BLOCK  EXR3A     IN = 114A  126     OUT = 116A    124
    BLOCK  EXR3B     IN = 114B  236     OUT = 116B    235
    BLOCK  MIX1      IN = 116A  116B    OUT = 116
    BLOCK  EXR2      IN = 112  124      OUT = 114   122
    BLOCK  R1A       IN = 122           OUT = 120   QR1A
    BLOCK  R1B       IN = 110           OUT = 112   QR1B
    BLOCK  COMP45    IN = 120           OUT = 110
;
;
FLOWSHEET   20K
    BLOCK  EXS2A   IN = 242A 224A       OUT = 244A 222A
    BLOCK  EXS2B   IN = 242B 234B-      OUT = 244B 232B
    BLOCK  EXS2C   IN = 212A 224B       OUT = 214A 222B
    BLOCK  EXS2D   IN = 212B 234A-      OUT = 214B 232A
    BLOCK  MIXC1   IN = 222A 222B       OUT = 222
```

Figure 2. ASPEN/SP simulation input file.

```
    BLOCK  SPLITC2 IN = 234              OUT = 234A  234B
    BLOCK  MIXC2   IN = 232A 232B        OUT = 232
    BLOCK  SPLITC1 IN = 224              OUT = 224A 224B
    BLOCK  SPLITH1 IN = 242              OUT = 242A  242B
    BLOCK  MIXH1   IN = 244A 244B        OUT = 244
    BLOCK  SPLITH2 IN = 212              OUT = 212A  212B
    BLOCK  MIXH2   IN = 214A 214B        OUT = 214
    BLOCK  EXS3  .  IN = 214  256        OUT =216 254
    BLOCK  S1A     IN = 222              OUT = 220  QS1A
    BLOCK  S1B     IN = 210              OUT = 212  QS1B
    BLOCK  S1C     IN = 232              OUT = 230  QS1C
    BLOCK  S1D     IN = 240              OUT = 242  QS1D
    BLOCK  COMP7   IN = 220              OUT = 210
    BLOCK  COMP6   IN =230             OUT = 240
    BLOCK  MIXTURB IN =254   235         OUT = 234
    BLOCK  TURB3   IN = 244              OUT = 246
;
;BLOCKS PARAGRAPH   4K REFER
;
BLOCK SPLITURB  FSPLIT
     FRAC 256  .6521
     BOPT  HMB-RESULTS=0
;
BLOCK  EXR5  HEATX
    ;SUBROUTINE UHE02N
    PARAM  5  0  AREA=4.1343  DPC=-0.01  DPH=-0.05
;    FLASH-SPECS  172   NPK=1  KPH=2
    FLASH-SPECS  128   NPK=1  KPH=1
    REPORT  CURVES
;
BLOCK  EXP1  COMPR
    PARAM  TYPE=3  PRES=2.05  ES=.7377
;
BLOCK EXR4  HEATX
    ;SUBROUTINE UHE02N
    PARAM  5  0  AREA=20.1219  DPC=-.01  DPH=-.1
    BOPT  RESTART=0
    FLASH-SPECS 118       NPK=1   KPH=1
    FLASH-SPECS 126       NPK=1   KPH=1
    REPORT  CURVES
;
BLOCK  MIX1 MIXER
;
BLOCK  EXR3A  HEATX
    ;SUBROUTINE UHE02N
    PARAM  5  0  AREA=10.7292  DPC=-.02  DPH=-.1
    FLASH-SPECS 116A       NPK=1   KPH=1
    FLASH-SPECS 124       NPK=1   KPH=1
    REPORT  CURVES
;
BLOCK  EXR3B  HEATX
    ;SUBROUTINE UHE02N
    PARAM  5  0  AREA=5.5104  DPC=-.02  DPH=-.1
    FLASH-SPECS 116B       NPK=1   KPH=1
    FLASH-SPECS 235       NPK=1   KPH=1
    REPORT  CURVES
;
BLOCK  SPLIT1  FSPLIT
   FRAC   114B  .34973
   BOPT  HMB-RESULTS=0
```

Figure 2. ASPEN/SP simulation input file (continued).

```
;
BLOCK  EXR2  HEATX
    ;SUBROUTINE UHEO2N
    PARAM  5  0  AREA=59.6061  DPC=-.02  DPH=-.1
    FLASH-SPECS 114        NPK=1   KPH=1
    FLASH-SPECS 122        NPK=1   KPH=1
    REPORT  CURVES
;
BLOCK  R1A  HEATER
   PARAM   PRES=-.04  TEMP=300.
;
BLOCK  R1B  HEATER
   PARAM   PRES=-.1  TEMP=80.
;
BLOCK  COMP45  HEATER
   PARAM    PRES=18  TEMP=300.
;
;
;BLOCKS PARAGRAPH  20K REFER
;
BLOCK  EXS2A  HEATX
    ;SUBROUTINE UHEO2N
    PARAM 5 0  AREA=6.2137  DPC=-.05    DPH=-.1
    FLASH-SPECS 222A       NPK=1   KPH=1
    FLASH-SPECS 244A       NPK=1   KPH=1
    REPORT  CURVES
;
BLOCK  EXS2B  HEATX
    ;SUBROUTINE UHEO2N
    PARAM 5 0  AREA=119.0726  DPC=-.03    DPH=-.1
    FLASH-SPECS 232B       NPK=1   KPH=1
    FLASH-SPECS 244B       NPK=1   KPH=1
    REPORT  CURVES
;
BLOCK  EXS2C  HEATX
    ;SUBROUTINE UHEO2N
    PARAM 5 0  AREA=50.473  DPC=-.05    DPH=-.05
    FLASH-SPECS 222B       NPK=1   KPH=1
    FLASH-SPECS 214A       NPK=1   KPH=1
    REPORT CURVES
;
BLOCK  EXS2D  HEATX
    ;SUBROUTINE UHEO2N
    PARAM 5 0  AREA=5.6267  DPC=-.03    DPH=-.05
    FLASH-SPECS 232A       NPK=1   KPH=1
    FLASH-SPECS 214B       NPK=1   KPH=1
    REPORT  CURVES
;
BLOCK SPLITC1 FSPLIT
      FRAC 224B .90
     BOPT HMB-RESULTS=0
;
BLOCK SPLITC2 FSPLIT
      FRAC 234B .9495
     BOPT HMB-RESULTS=0
;
BLOCK SPLITH1 FSPLIT
      FRAC 242B .9440
     BOPT HMB-RESULTS=0
;
```

Figure 2. ASPEN/SP simulation input file (continued).

```
BLOCK SPLITH2 FSPLIT
      FRAC 212A .9094
     BOPT HMB-RESULTS=0
;
;
BLOCK MIXH1  MIXER
;
BLOCK MIXC1 MIXER
;
BLOCK MIXH2  MIXER
;
BLOCK MIXC2 MIXER
;
BLOCK EXS3  HEATX
    ;SUBROUTINE UHE02N
    PARAM 5 0 AREA=15.3040  DPC=-.02   DPH=-.05
    FLASH-SPECS 254        MPK=1   KPH=1
    FLASH-SPECS 216        MPK=1   KPH=1
;
BLOCK  S1A       HEATER
     PARAM      PRES=-.05  TEMP=300.
;
BLOCK  S1B       HEATER
     PARAM      PRES=-.1  TEMP=80.
;
BLOCK  S1C       HEATER
    PARAM     PRES=-.05  TEMP=300.
;
BLOCK  S1D       HEATER
     PARAM      PRES=-.1  TEMP=80.
;
BLOCK COMP6  HEATER
     PARAM       PRES=8.2  TEMP=300.
;
BLOCK  MIXTURB   MIXER
;
BLOCK COMP7  HEATER
     PARAM       PRES=2.7 TEMP=300.
;
BLOCK TURB3  COMPR
     PARAM  TYPE=3     ES=.76   PRES=2.1
;
;STREAM PARAGRAPH
;
;
;
;STREAM  Z36    PRES=2.1   TEMP=16.75   MASS-FLOW=.1319
;   MOLE-FRAC  HELIUM  1.0
;
STREAM  182    PRES=.8    TEMP=3.996   MASS-FLOW=.24892
   MOLE-FRAC  HELIUM  1.0
;
STREAM  112    PRES=17.9    TEMP=80   MASS-FLOW=.24892
   MOLE-FRAC  HELIUM  1.0
;
STREAM  114    PRES=17.8    TEMP=25.5   MASS-FLOW=.24892
   MOLE-FRAC  HELIUM  1.0
;
;
STREAM  116    PRES=17.7    TEMP=17.5   MASS-FLOW=.24892
```

Figure 2. ASPEN/SP simulation input file (continued).

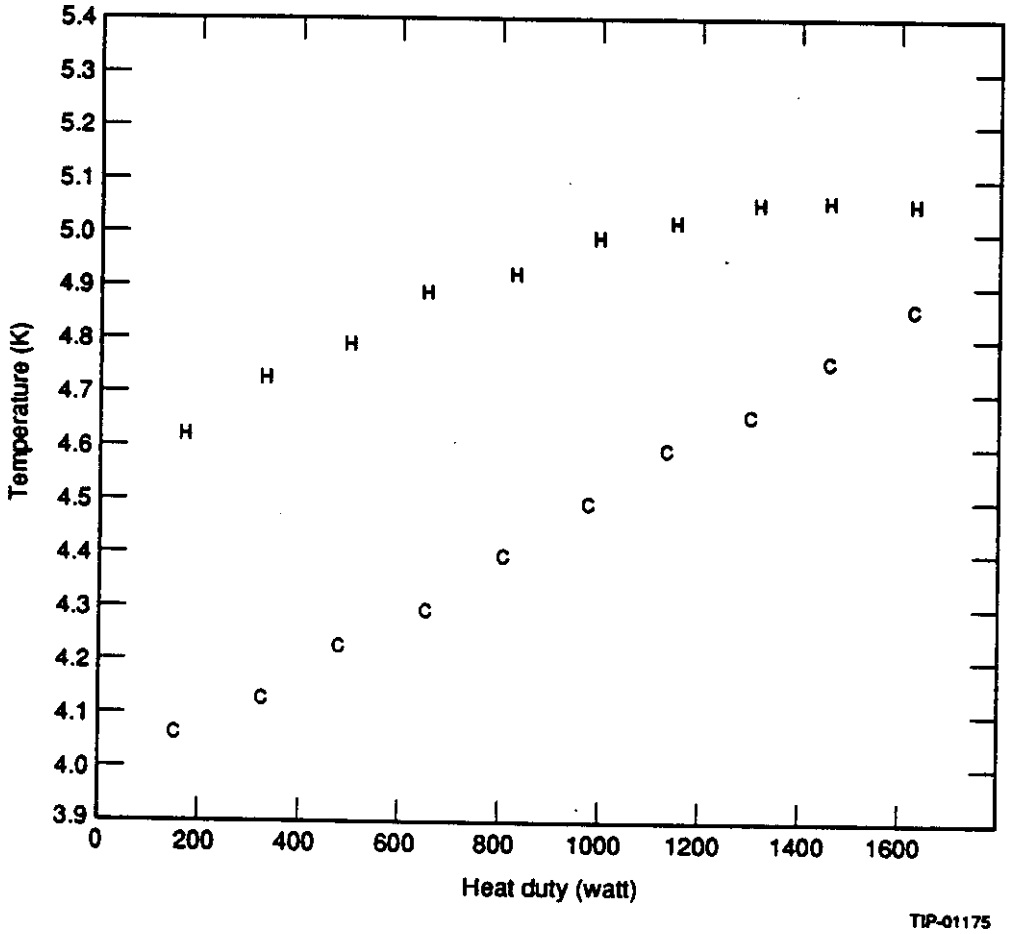

Figure 3. Plot of Temperature Profile in Heat Exchanger EXR5.

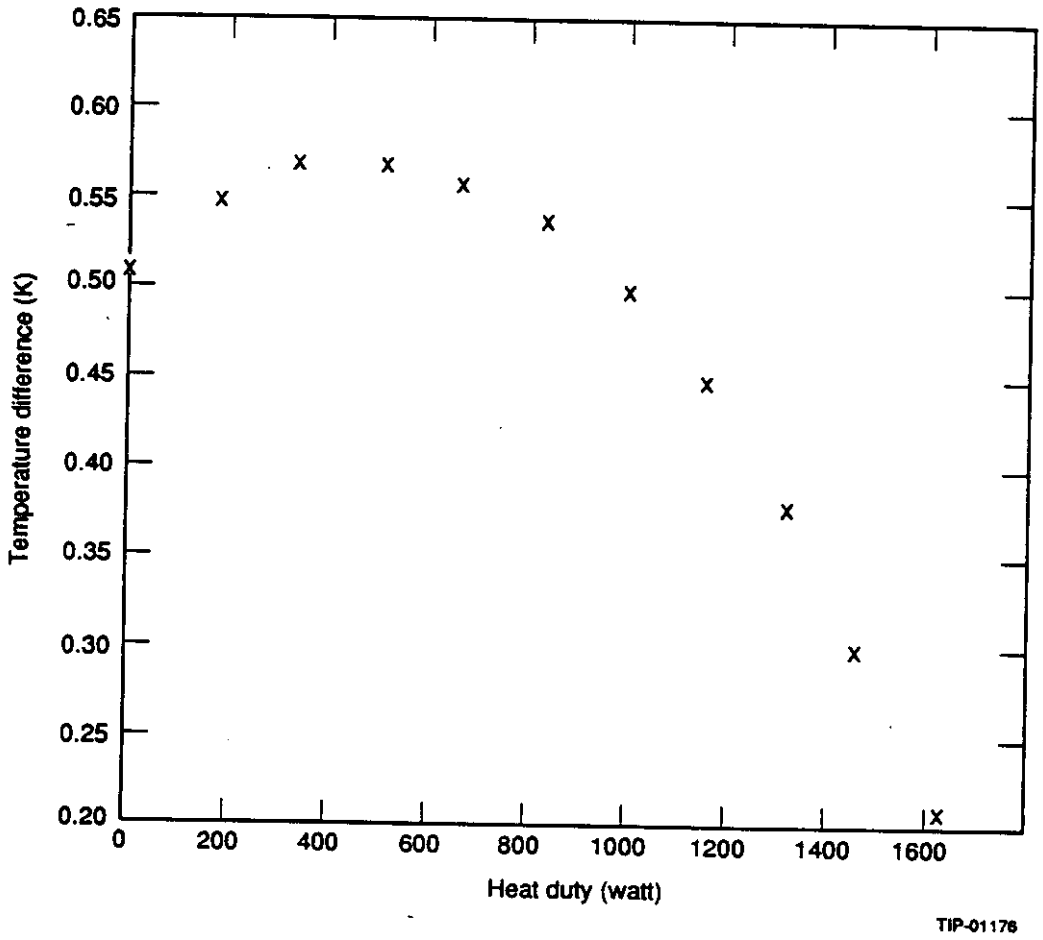

Figure 4. Plot of Temperature Difference Profile in Heat Exchanger EXR5.

SIMPLIFIED CRYOGENIC REFRIGERATION CYCLE
STREAM SECTION

256	236	172	128
FLOW DETAILS	256	236	172	128
COMPONENT FLOWS <KMOL/SEC>				
NITROGEN	0.0	0.0	0.0	0.0
HELIUM	0.0617	0.0329	0.0621	0.0621
TOTAL	0.0617	0.0329	0.0621	0.0621
PHASE SPLITS				
VAPOR FRACTION <MOLE BASIS>	1.0000	1.0000	0.0	1.0000
LIQUID FRACTION <MOLE BASIS>	MISSING	MISSING	1.0000	0.0
SOLID FRACTION <MOLE BASIS>	MISSING	MISSING	0.0	0.0
INTENSIVE PROPERTIES				
TEMPERATURE <K>	16.7322	16.7322	4.5034	4.8731
PRESSURE <ATM>	2.1000	2.1000	2.0000	0.7900
MOLECULAR WEIGHT	4.0030	4.0030	4.0030	4.0030
ENTHALPY <J/KMOL>	-.58562+07	-.58562+07	-.62110+07	-.61100+07
ENTROPY <J/KMOL-K>	-.66360+05	-.66360+05	-.11112+06	-.85263+05
DENSITY <KMOL/CUM>	1.5445	1.5445	31.1068	2.3222

Figure 5. Excerpt of the stream report for the simulation that contains hot water outlet stream from EXR5.

CONCLUSIONS

Our work has demonstrated that reliable, predictive simulation models of the cooling sector of the SSC can be developed with ASPEN/SP. Verification and preliminary optimization of individual designs also has proven feasible via the simulation models. Finally, the simulation models have proven useful for the performance of rudimentary cost-benefit analyses of competing process designs. The ability to perform meaningful off-design and optimization studies is somewhat limited due primarily to the inadequacies of the multiple stream heat exchanger and compressor-turbine unit operation models.

RECOMMENDATIONS FOR FUTURE WORK

While the modeling work has been successful and has served most of the desired purposes, a few additional enhancements would prove quite useful for process optimization and studying the performance at off-design conditions. The first of these enhancements is a simplified equation of state for helium, which executes faster than the McCarty model with no significant loss of accuracy. Air Products has developed a proprietary implementation of such a model, although a thorough study of the accuracy and robustness of the model has not yet been performed. A second desirable enhancement is a compressor - turbine model which is capable of performing fairly sophisticated rating calculations, including the prediction of choke flow conditions and off-design efficiencies. Such a model is essential for off-design si3ulations. A third recommended enhancement is the addition of an axial heat conduction calculation to the two stream heat exchanger. Axial conduction is significant due to the geometry of the cryogenic exchangers employed. A final recommended enhancement is a more rigorous multiple stream heat exchanger model, which considers the area distribution inside the exchanger. Such a model would be very useful in optimizing heat exchanger design and in predicting off-design performance.

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